Predicting the Distribution and Properties of Buried Submarine Topography on Continental Shelves

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LONG-TERM GOALS

Compile geological data and develop methods to predict the distribution and properties of features hypothesized to be responsible for sonar geoclutter. Geological structures just beneath the seafloor, such as steep-walled channels, may have high-angle reflecting surfaces that can return false sonar alarms to ships operating in the littoral zone. The major goal is to contribute to the reduction or mitigation of geologic clutter observed on fleet sonar systems.
Two issues define the problem.

- Landscape forming issue: In area ‘x’, can the Navy expect geoclutter features and if so what are their sonar characteristics, i.e. channel orientation.

- Landscape burial issue: If geoclutter features are expected in area ‘x’, will the features be exposed or buried. Areas of low interest to the Navy include locations where Holocene deposits are thick. Areas of high interest to the Navy include locations where Holocene deposits are thin thereby allowing for the shallow burial of Pleistocene topography.

OBJECTIVES

- Develop a global atlas of candidate geoclutter features and their characteristics.

- Develop and merge global databases of pertinent geological and oceanographic data.

- Develop predictive models and apply to margins of interest. Test predictive models in a known geoclutter rich area.

APPROACH

1. *Compile a global database of pertinent geological and oceanographic data,* for use as initial inputs and constraints for sediment flux models (*HydroTrend* and *SedFlux*).

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14. ABSTRACT
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2. *Measure and analyze terrain attributes.* Perform a comprehensive analysis of real and simulated elevation grids using RiverTools® and other GIS software. Calculate the geometric and statistical characteristics of landforms and how these characteristics vary from one geologic setting to another.

3. *Classify terrain from geologic information.* Classify "terrain types" in terms of the initial and boundary conditions (e.g. geology, erosion rates, excess rain rates) that produced the terrain types, using physics-based landform models.

4. *Determine the burial depth potential of low-sea level produced topography.* Develop simple scaling relationships for deposition rate as a function of sediment input rates from rivers, wave and current conditions, and shelf geometry. Refine these bulk estimates with more detailed consideration of the nature of sediment delivery to the shelf (e.g., episodic storm-driven flooding vs. seasonal snowmelt flooding; the role of estuaries) and sediment redistribution, bypassing and deposition on the shelf (e.g., the long-term manifestation of short-term, episodic, storm-driven transport on the shelf).

5. *Model the flux of sediment to and across continental shelves.* Use process-based models (*HydroTrend*) to obtain a detailed consideration of the nature of sediment delivery to the shelf and sediment redistribution, bypassing and deposition on the shelf.

WORK COMPLETED

1) Syvitski calculated wave power (Fig. 1) for the global ocean database on ocean wave characteristics (height, period, direction) and wind force, based on NOAA's WaveWatch III (Fig. 1). WW3 solves the spectral action density balance equation, and includes refraction and straining of the wave field due to temporal and spatial variations of the water depth and currents (e.g. tides, surges). WW3 tracks both the swell and wind wave component of the total wave field. NOAA's NCEP Reanalysis recovers the ocean wave climatology over the last 7 years at a temporal resolution of 3 hours.

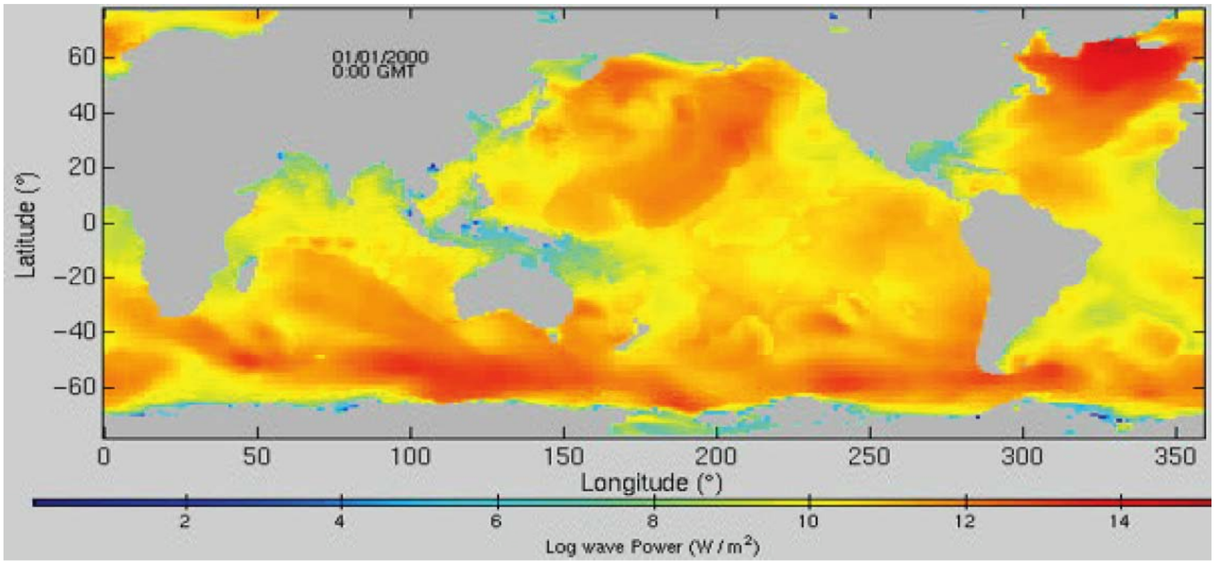

Figure 1. Global map showing wave power in W/m^2 based on WaveWatch III (0.5° x 0.5°) data. Image is for January 1, 2000, 0:00 GMT. A large storm has increased the wave power (>14W/m^2) in the North Atlantic. Sea ice shows as land in the image, and thus Bering Sea is seen as land.

2) Syvitski added global runoff to the global river database, along with drainage basin temperature, precipitation, evapotranspiration. The database is used as inputs to INSTAAR sediment flux models. Runoff is based on a mixture of data from the Global Runoff Data Center (GRDC) and the UNH Water Balance Transport Model (WBTM) (Fig. 2). The former covers 72% of the land surface draining into oceans, and the later covers the remaining 28%. Predicted the monthly and yearly discharge of these global rivers as an aid to understanding where shallow burial of paleo river channels could be considered likely.

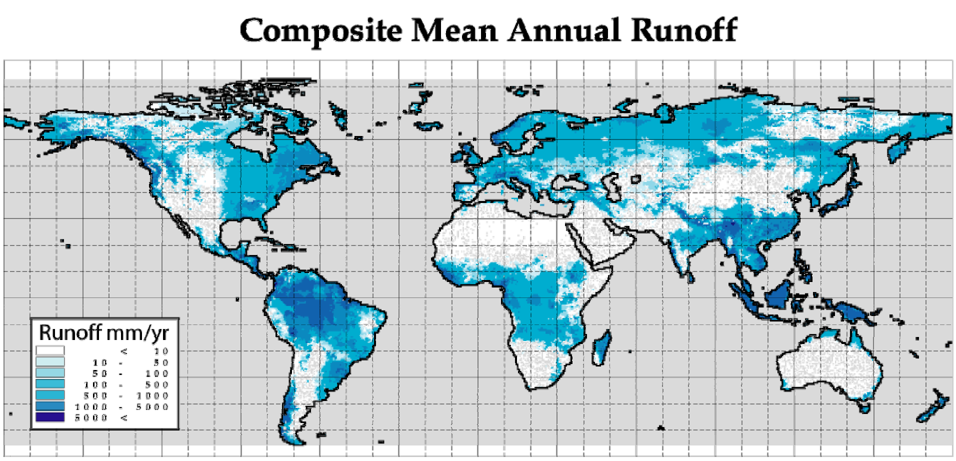

Figure 2. Map of global runoff in mm/yr based on a mixture of observations (GRDC) and modeling results (WBTM) (0.5° x 0.5°). Image is a 35-y composite based on monthly values. Darker patterns show high runoff areas such as the intratropical convergence zone centered at the equator.

3) Syvitski verified the ART model as a predictor of prehuman sediment discharge against 28 pristine rivers, or rivers with loads measured before the dominating impact of humans (Fig. 3: Syvitski et al., 2005).

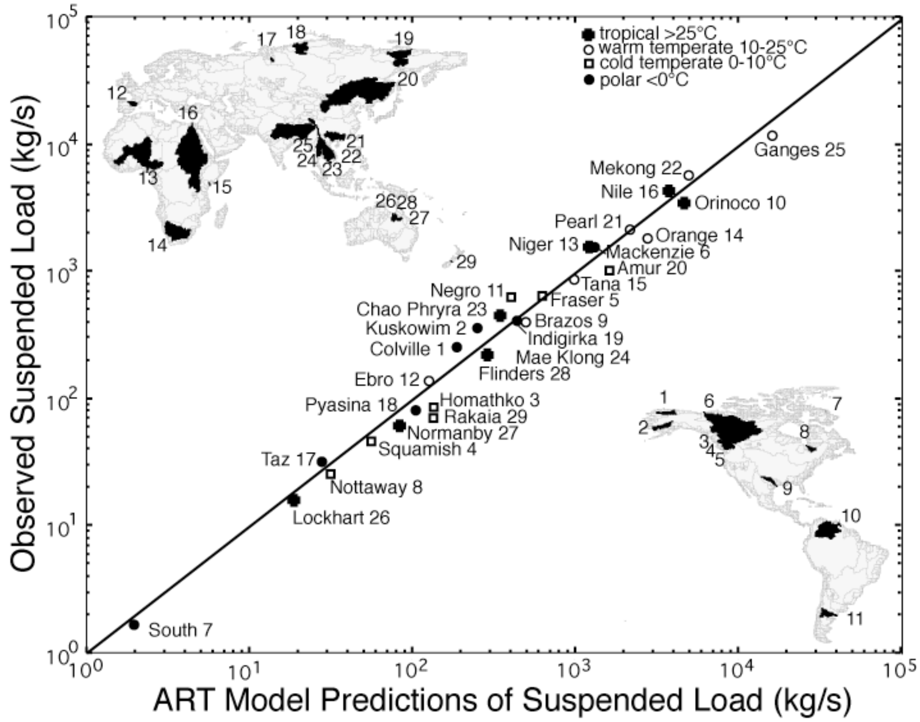

Figure 3. Comparison of sediment load observations with ART model predictions for selected pristine (largely unregulated) rivers (e.g. South, Colville, Indigirka, Pyasina, Squamish, Kuskowim, Mae Klong, Orinoco), or rivers with observations before major human impacts (e.g. Nile, Ebro, Orange). Largest difference between predictions and observations is 63% (Negro River). Errors associated with observational data are of the same magnitude as those associated with predictions.

4) Peckham analyzed mathematical and numerical models for fluvial landscape evolution, focusing on the geomorphic rain-rate a key parameter in every fluvial landscape evolution model. The rain-rate value, though rarely attained, must occur often enough to make significant changes to the landscape. We had originally proposed to perform a large number of simulations in which the input parameters were systematically varied and the results catalogued in an attempt to discern the important trends. While this "brute force" or Monte Carlo numerical approach can yield useful results, approaches based on a mathematical analysis of the model equations, when tractable, yield superior results and lead to a deeper understanding of how model output is determined by the input parameters. The brute force approach was not feasible for this problem because the computer time required by available landscape evolution models to generate sufficiently large DEMs was prohibitive. Simulated DEMs with at least 500 columns and 500 rows (and preferably much larger) are necessary to get embedded river networks large enough for geometric properties to be measured with sufficient accuracy. Peckham modified UVA's Fortran model to produce larger DEMs, but the model took several months to generate even one DEM of the required size. Adaptive time-steps are used for numerical stability and these can become extremely small in the case of a large DEM. Contrary to our initial hypothesis, it is not the costly requirement of

computing a new area grid for each time-step. Peckham wrote a new fluvial landscape evolution model similar to UVA's which, though faster, was still not sufficiently fast to numerically explore the model's parameter space. Work is ongoing to find ways to make these models run much faster while maintaining numerical stability. The problem is far from straight forward and will require further research.

5) Peckham analyzed a steady-state fluvial landscape model with mathematical methods. Analyzing a steady-state equation is reasonable in that the numerical models are generally run until the landscape reaches a quasi-steady state. This effort met with a much greater level of success. In particular, it was found by scaling analysis that the effect of changing the geomorphic rain-rate, R, while holding all other parameters fixed is to vertically rescale the resulting landscape surface (and hence all slopes) by the factor $(1/R)$. As a result, it is unnecessary to systematically vary the parameter R (when it is treated as spatially constant) in numerical solutions because the effect of doing so can be predicted in advance.

RESULTS

Due to sea-level rise over geologic timescales, there are places where a channelized coastal plain is now buried in mud on the continental shelf. In places where the mud layers are not too thick, the former landscape surface may generate acoustic return signals that are similar to those of submarine vessels. The purpose of this project was to perform fundamental research on the geometry of fluvial landscapes that might eventually lead to methods for distinguishing between these two types of signals. It should be noted, however, that we were not tasked with the problem of comparing actual acoustic signals from these alternate sources, or in fact with making any type of prediction regarding the acoustic signals themselves. Our task was instead to determine the feasibility of predicting

(1) the likely depth of overlying mud layers and

(2) various geometric features of the now mud-buried paleo-landscape, for the portion of the continental shelf just offshore of a given location. A challenging aspect of this project was that we would have little measured data for directly validating our predictions.

One approach to predicting geometric features of a paleo-landscape is to assume that the landscape that currently lies directly onshore from a given location is not significantly different and can therefore be used as an analog. However, there are several implicit assumptions in this approach, such as

1) geology and lithology are the same at the corresponding onshore and offshore locations,

(2) so-called geomorphic rain-rates have not changed during the time of sea-level rise,

(3) vegetative cover of the paleo-landscape was similar to that of the current landscape.

While each of these assumptions is questionable, this approach provides a reasonable null hypothesis. It would be straight forward for future researchers to generate acoustic signals or make geometric measurements using DEMs of the current (onshore) landscape for comparative purposes. It must be emphasized, however, that the geometric features of the fluvial landscape that are most likely to produce the acoustic signals of interest are at a scale that is smaller than the grid spacing of most currently available DEMs. In addition, most fluvial landscape evolution models do not attempt to simulate the geometry within channels, but operate at the larger scale of valleys and hillslopes and use relatively large-grid spacing. In order to say anything about channel geometry, it is therefore necessary to use equations that relate the attributes of basin-scale geometry – such as contributing area, bankfull discharge and valley slope – to the attributes of channel-scale geometry, such as width and depth. The well-known empirical equations of hydraulic geometry, which have some support from theory, allow the bankfull channel width and depth to be expressed as a power-law function of the bankfull discharge. The bankfull discharge, in turn, can be estimated from the basin contributing area and the geomorphic rain-rate. The geomorphic rain-rate cannot be measured directly but must be estimated.

Whether the geology and lithology at an offshore and corresponding onshore location are the same or not is something that can, in principle, be determined from measurements, such as a core from the offshore location. If the geology is the same, then statistical differences between the current landscape and the paleo-landscape must be due to differences in the geomorphic rain-rate and/or the vegetative cover at the times the two landscapes were evolving. If the geology is different, then it may be possible to find another onshore location with similar geology that could be used for comparison.

A closed-form, parallel-rill solution to the steady-state fluvial landscape equation was found that shows that the width of these rills varies with the slope of the rill channels, S, and the geomorphic rain-rate, R, as $w = q_1 / (S\,R)$, where q_1 is a fixed parameter. This result is consistent with the general scaling result just described because changing R by some factor results in a compensating change in S and no net change in the width or plan-form geometry. Another result was that for the realistic case g= -1, where gamma is the exponent relating slope to unit-width discharge (and which produces longitudinal profiles that are logarithmic), any R=0 solution, $f(x,y)$, to the steady-state landscape equation can be transformed into a R>0 solution, $g(x,y)$, via the simple transformation $g(x,y) = (-1/R) \log[f(x,y)]$. This general result for a nonlinear partial differential equation is rare in mathematics (Peckham 2003a, 2003b). The numerical problem can also be simplified dramatically since the case where $R=0$ is much more stable. Note that the case g= -1 corresponds to the case where $n = 2(m-1)$, where m and n are the exponents in the sediment transport law. This includes the case $(m,n) = (2,2)$ and other cases like $(m,n) = (3/2,1)$, in which both m and n are between 1 and 2.

Our modeling efforts show that the value of R is recorded in the geometry of the landscape and can be estimated locally as a function of the elevation values in the immediate vicinity of any given point. The ability to estimate R from local elevation values suggests that spatial variation in R, due to effects such as orography can also be read from the landscape (Peckham 2003b). Inverse methods have been developed to estimate the geomorphic rain-rate from DEM-extracted longitudinal profiles and from parallel-rill geometry. Similar results allow us to place constraints on the exponents m and n, and show how topographic or bathymetric (paleotopography before sea-level rise) data can be used to estimate or constrain some of the key parameters in fluvial landscape models.

Burial of river channels carved into the shelf seafloor during periods of lower sea level depends largely on the pre-human sediment flux. By verifying that our sequence of models provides for an estimate of the pre-human burial of Pleistocene channels on continental margins, and by modeling the dispersal of seafloor sediment through the proxy wave power, then we provide a means of estimating the geoclutter potential of global shelves (Fig. 4). Areas of high sediment flux (i.e. > 10MT/yr) should not be considered as sites where shallow burial of Pleistocene channels would not produce sonar geo-clutter:

the channels are too deeply buried. Such coasts are found off the Amazon, Magdalena, Parana, and Orinoco rivers of South America, the Mississippi, Eel, Yukon, Fraser and Cooper rivers of North America, the Ganges, Mekong, Red and Yellow rivers of South Asia, and off many of the Islands comprising the Philippines, Indonesia and Taiwan. Where the dispersal energy is high by tides (e.g. Yangze, Fly, Indus rivers), by currents (e.g. Adriatic, Gulf of Lions), or by waves (e.g. much of the coast of India) the chance of sonar clutter from shallow buried channels is considered to be higher.

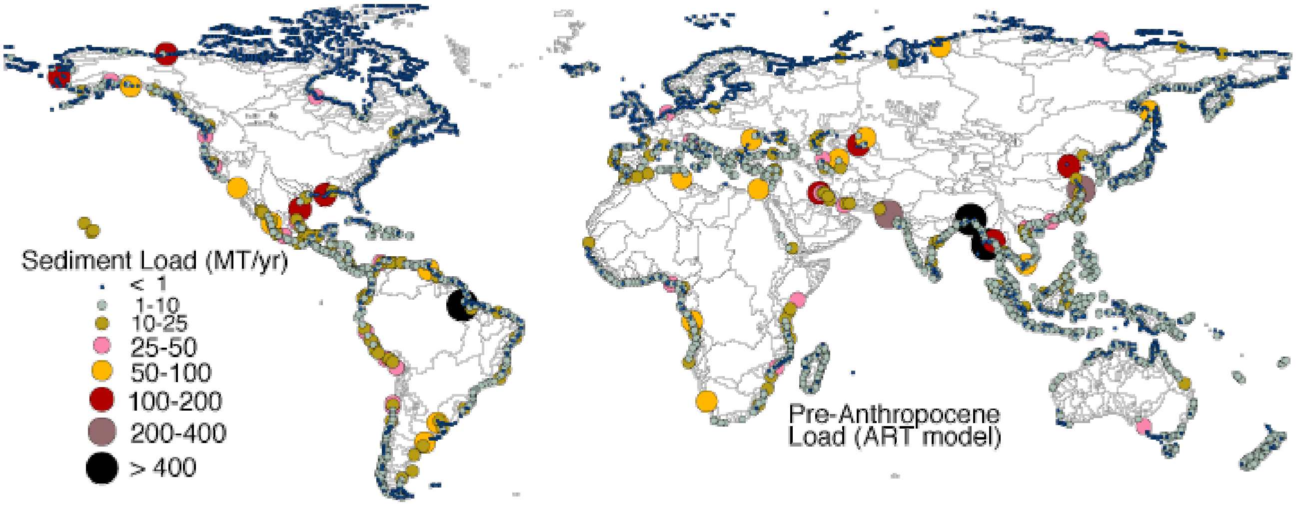

Figure 4. Map of the world showing sediment load in MT/yr predicted for≈4400 river basins based on the ART model (Syvitski et al., 2005).

IMPACT/APPLICATIONS

The acoustic community and geophysical community including modelers, must determine more specifically, the exact nature of the sonar clutter, and how much of the clutter is from features within the channels or the channel walls, to further support this effort.

RELATED PROJECTS

- ONR EuroSTRATAFORM: Modeling the Effect of Climatic and Human Impacts on Margin Sedimentation. (http://instaar.colorado.edu/deltaforce/projects/euro_strataform.html)

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